PROOF OF A CONCEPT FOR PERMEABLE INTERLOCKING CONCRETE PAVERS DESIGNED FOR RAPID RESTORATION OF INFILTRATION

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ABSTRACT

Where clogging of drainage cells in permeable interlocking concrete pavers (PICPs) is dominantly in the upper parts of the filter media, as it is in most cases, the cells in special PICPs may be very rapidly cleaned (and restored), provided that the PICP design is dovetailed to the surficial fluid mechanics of the street cleaning equipment. PICPs described in this paper have special-purpose cupules designed and made for rapid cleaning, connected to drainage conduits designed for and providing high infiltration. Cupules facilitate rapid and thorough removal by routine street cleaning equipment operating at reasonable speeds. Geometry of the resulting drainage cell also meets the requirements of the American Disability Act as well as unstated requirements for mass production.

To develop these special PICPs – denoted RCPP (Rapidly Cleaned Permeable Pavers) - experiments were carried out in Guelph, Ontario. In the experiments, the independent variables were: *V* speed of cleaning equipment over the pavement; *theta* angle of the cleaning jets; *v* air velocity in the jets; *d* and *phi* geometry of the cupules; *w* width of drainage conduit; and *G* gradation of the filter media. *S*, the ratio of mass of removed and captured to original mass of cell filter media (plus filtrate), is the dependent variable. Results obtained in a laboratory rig show that, for the chosen geometries, complete removal *S* = 1.0 is easily achieved at almost any reasonable speed *V*.

The essential result is that particulates and pollutants associated with them are readily captured from these new RCPP by routine regenerative-air street cleaning equipment.

INTRODUCTION

Whereas impervious areas are associated with increased flows and contaminant concentrations and loads, permeable pavers, by allowing water to infiltrate into the subsurface layers, have an effect that tends towards imitation of pre-development hydrologic regimes - they not only reduce surface runoff and recharge groundwater (or capture stormwater for reuse) but may reduce pollutants reaching receiving waters (Schueler, 1987), including heat (such as solar thermal enrichment).

Whether planning, designing, constructing and/or managing a permeable pavement installation, it is fundamentally important to provide and *maintain* surface infiltration capacity - allowing an adequate volume of stormwater to be captured and treated by the facility. Permeable paver infiltration capacity is dependent upon factors such as drainage cell density and permeability; surface slope; surface ponding; pavement base permeability, drainage and void volume; grading and quantity of surface dust and dirt applied; duration and intensity of surface loads (such as traffic); and, above all, *proper pavement management*. Designing and constructing a new system to provide appropriately high infiltration capacities is not problematic, but maintaining infiltration capacities over several or many years has proven to be a concern, if not actually challenging.

In the past, continuing maintenance of PICPs has tended to the haphazard, rather than easily routine. This is the nub of our new pavers.

The earlier work reviewed below is predominantly our own, publications of which are freely available in the public domain through the Journal of Water Management Modeling (JWMM). A longer, more detailed version of this paper is being published in JWMM. Readers may access the journal at https://www.chijournal.org/ and search for relevant papers by entering a simplified search term, "PAV" for instance.

EARLIER WORK

Thompson and James (1994 and 1995) described the design, construction and instrumentation of four different pavements - asphalt (AS), concrete brick (CP), and three-and four-inch thick concrete paver stones with infiltration cells (E3 and E4) – that were installed in both a typical parking lot and in a laboratory rig, for studies of the flux of 23 contaminants, including heat. In a follow-up paper, James and Thompson (1997) report conclusions obtained from the parking lot pavements after the first year. Some of their results are given in Figure 1. Their test pavements and laboratory rigs were used in much of the ensuing research reported below.

In their research, Shahin (1994), Thompson and James (1995), and James and Verspagen (1997) found low runoff volumes from the upper free surface of permeable concrete pavers in laboratory tests. Of course, laboratory test blocks were not subjected to wear or pollutant deposition on the PICP surfaces and, therefore, performed under optimum conditions. Kresin, James and Elrick (1997), on the other hand, collected data at several existing outdoor Uni-Ecostone permeable concrete paver installations, and tested the hypotheses that infiltration capacities decrease with age and certain land uses, and were improved by street sweeping and/or vacuuming the surface. They showed a significant relationship between overall effective infiltration capacity (fEo) and pavement age: as Uni-Ecostone installations aged, fEo decreased. Also significant is the relationship between fEo and the degree of compaction (defined as travelled or untravelled). fEo can be improved by removal of the top layer of external drainage cell (EDC) material, which they denoted the EDC crust. Additional conclusions drawn from their results include:

1. Infiltration capacity of the EDC crusts was lower than for the cell, and found to be significantly affected by age.
2. fEo may be regenerated by street sweeping and/or vacuuming the Uni-Ecostone surface.
3. fEo was affected to a greater extent by EDC fines content than organic matter (OM) content.

Much later, the then eight-year old installation of two different types of permeable pavements in the parking lot were studied between May and September 2001, by James and Gerrits (2003), concentrating on the decrease in infiltration capacity with age and increased traffic use, as well as methods of restoring the infiltration capacity of permeable pavers, e.g. by street sweeping and/or vacuuming the surface. They confirmed the by-then obvious fact that, as permeable-paver installations age, and/or are heavily used, infiltration capacity decreases due to clogging of the external drainage cell (EDC) with fines (silt and clay), organic matter and extractable solvents from automobiles (primarily oil and grease). No pavement maintenance procedures were used over the 8 y period, other than snow removal, and street sweeping with rotating brushes annually in spring. Infiltration rates were tested before and after material was extracted from the EDCs and subjected to a particle size and constituent analysis. Extracted material was tested for a number of different organic and chemical constituents, such as heavy metals, nutrients and organic matter. Results once again confirmed that infiltration capacity decreased with increasing average daily traffic counts, and as the amount of organic matter and fine matter in the EDC material increased. Furthermore, the tests indicated that the infiltration capacity can be significantly improved by removing only the top 10-20 mm (0.4-0.8 inches) of EDC material; a removal depth that might be achieved under certain conditions. Results are shown in Figure 1. It could be argued that much of the later research, including that reviewed here below, serves to confirm the findings in this figure.

Summarising, they found that infiltration rates for modular interlocking permeable pavers with open drainage cells were:

1. spatially variable, and dependent on: pavement usage, percentage of fine matter in the EDC, the test-installation bedding layer gradation, and – to a lesser degree – the percentage of volatile organic matter in the EDC.
2. greatest in the ultra-low average daily traffic (denoted low ADU) area, where regeneration to the maximum infiltration capacity (MIC) could be accomplished by removing as little as the top 15 mm of EDC material. In the medium-low CP area MICs were found to be less than the ultra-low CP area (regeneration to the critical infiltration capacity could not be reached by removal of the top 25 mm of EDC material - results suggest that this might be possible with removal of more EDC material, while some degree of regeneration was noted at all excavation depths); These infiltration rates were also found to be the lowest in the low CP area, where only a minimal amount of regeneration could be obtained.
3. higher, and regeneration could be reached by removing less EDC matter, in the MICBEC3 installation; in the MICBEC4 installations MICs were much lower initially and regeneration to the critical infiltration capacity was not obtained for any test plot.
4. lower for the plots that had water ponded on them for more than one hour after a storm event, as compared to plots where the water did not pond. The percentage of fine matter in the EDCs was found to be slightly greater in the top 5 mm and approximately equal for all other depths. The percent of volatile organic content (%VOC) was found to be significantly higher in the frequently flooded plots, for all depths, not just the upper 5 mm.
5. %VOC in the EDCs was found to be similar for both installations and all traffic uses. Plant material (measured as %VOC) was found to be much greater for the vegetated plots, under large coniferous tree along the grass verge. Infiltration rate was not found to be greatly affected by the %VOC, with the exception of plots where the %VOC was significantly greater than the average %VOC. In this case, the infiltration rate was found to be an order of magnitude greater than the non-vegetated area.

James (2004) studied clogging of permeable interlocking concrete block pavement (PICPs) in a full-scale outdoor test rig. Samples of parking lot dust and dirt (D&D) were collected from existing PICP installations and processed to remove moisture and volatile compounds. Samples were then analyzed for their particle size distribution. City street D&D was collected in large quantities, processed and reconstituted into the same fractions found on the permeable paver surface. Tests were then conducted on a special outdoor rig. Synthesized D&D and artificial, intense rains were systematically applied to the pavement, and surface and subsurface drainage flow rates measured. Four different PICPs were tested, and drainage cell, bedding and base material throughout the test pavement were sampled and analyzed.

Change in the performance (infiltration rates) of the permeable pavers as a result of the sediment application did not begin immediately. Quantities of sediment that can be applied without causing a decline in performance of the pavers were evidently determined by the porosity of the drainage cell fill material and of the applied sediment. After the application of 1.4 kg/m^2 of total suspended solids (TSS), the average infiltration rate at the paver surface may decline to a rate below the inflow rates (using a 1/25y design storm of 5-min duration with an intensity of 230 mm/h). More frequently observed rainfall events with lower rainfall intensities might produce different results. After the accumulation of 3.9 kg/m^2 of TSS, the drainage cell material may become functionally clogged. However, over a large section of permeable pavers, heterogeneity of the infiltration rates over different sections may uphold the performance of the pavers for some time. MICBEC permeable pavers should be properly maintained when there is a risk that the surface is affected by partial clogging. This should correspond to the accumulation of between 1.4 to 3.9 kg/m^2 TSS. James recommended that his results be compared to similar experiments using different drainage cell and base materials of varying porosity, and using different rainfall intensities and durations.

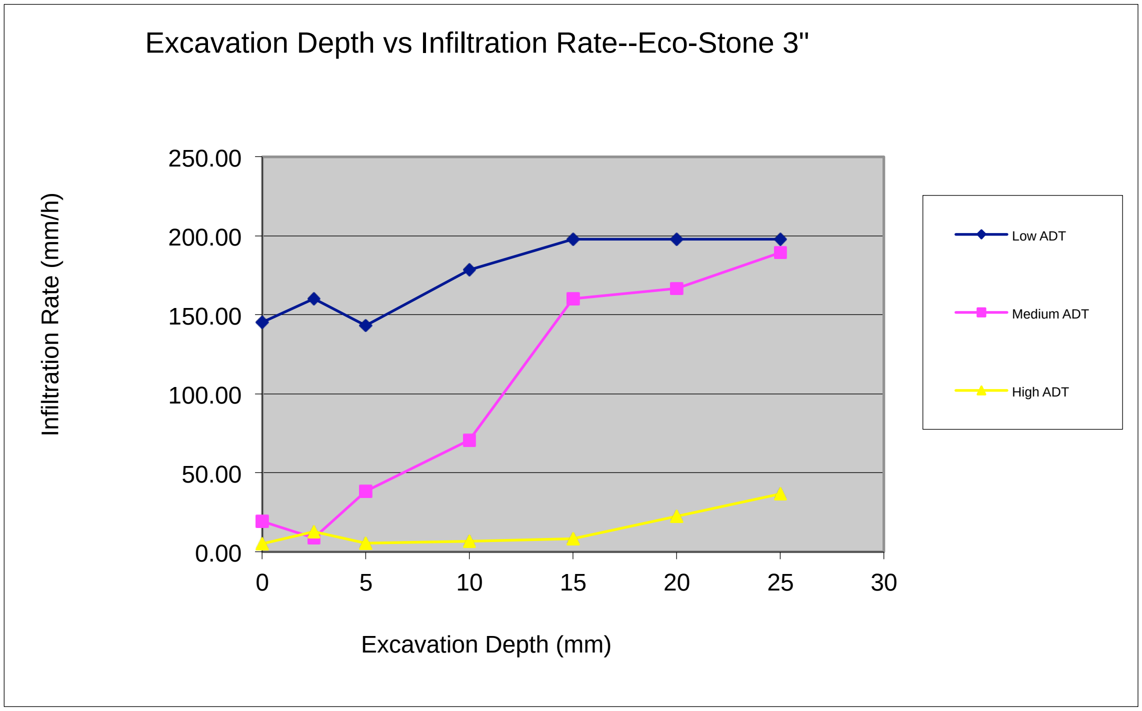

Figure 1 Infiltration capacity vs depth for MICBEC3 installation. Max rain rate was 200 mm/h

Bean, Hunt and Bidelspach (2005) tested the surface infiltration rate of 27 permeable pavement sites in North Carolina, Maryland and Delaware. One site was monitored to compare pollutant loads of asphalt runoff to those in the collected infiltrate. Concrete grid pavers (CGP) and permeable interlocking concrete pavers (PICP) were tested with pavement ages ranging from 0.5y to 20y. They conducted two infiltration tests on 14 CGP lots filled with sand: (a) on the existing condition of the surface and (b) after the removal of the top layer of residue (13 - 19 mm). Unsurprisingly, their pseudo-maintenance improved the median average infiltration rate on 13 of 14 sites at a confidence level of 99.8% from 50 mm/h to 80 mm/h. Eleven PICP sites were also tested, and they predictably found that sites built near a source of loose fine particles had infiltration rates significantly less than sites free of loose fines, with observed averages of 600 mm/h and 20,000 mm/h respectively - even the minimum existing infiltration rates were comparable to those of a grassed sandy loam soil.

In a Canadian study, Drake and Bradford (2013) once again reiterate that removal of surface material in drainage cells restores infiltration. However, previous removal methods having been limited to small-scale testing, they present the results and experiences of using regenerative-air and vacuum-sweeping trucks on existing permeable pavements in Ontario. A regenerative-air truck was used on two parking lots with well-used permeable interlocking concrete pavers and pervious concrete while a vacuum-sweeping truck was tested on a third parking lot with permeable interlocking pavers. Both systems provided partial rehabilitation of the permeable pavements. They confirmed the finding of James and Gerrits (2003) that "post-treatment" surface infiltration rates on all three parking lots displayed large spatial variability, and they suggested that micro-conditions confound overall effectiveness of maintenance. Drake and Bradford self-evidently suggest that maintenance may be improved by regular cleaning and by developing instructional guidelines for pavement owners and equipment operators. They state that the street cleaning equipment used in their study will undoubtedly be more effective on PPs with less severe clogging, and recommend their application for preventative maintenance, subject to further research to optimize maintenance procedures. Their observations have been reworked by the present authors.

The Toronto Regional Conservation Authority (TRCA, 2015) monitored a parking lot that was constructed with conventional asphalt, pervious concrete and two types of PICP: UNI-Optiloc with a joint width of about 25 mm, and AquaPave having a joint width of about 13 mm. Study findings from their Phase II Full Report "Five Year Evaluation of Permeable Pavements" are also unstartling: *"… permeable pavements are an effective practice for maintaining or restoring infiltration functions on parking lots and other low volume traffic areas, even in areas with low permeability soils… Vacuum cleaning … partially restored permeability to the pavements... It is not yet clear how effective vacuum cleaning will be in reversing clogging on this type of pavement."*

Readers may well ask where these largely repetitive findings have lead us. Kipkie and James (2000) examined the feasibility of code for the US EPA Storm Water Management Model (SWMM) to allow planners and designers to simulate the responses of permeable pavements in long-term modeling applications. Infiltration capacity of the permeable pavers was based on available studies, taking into account degradation over time and regeneration by mechanical means. James, James and von Langsdorff (2001) later detailed the underlying method and function of a free-ware program that also used SWMM (and PCSWMM) for the design of permeable pavements and was also based on the sum of James' research reviewed above. Later, SWMM5 incorporated similar routines, which have enjoyed wide use.

CURRENT RESEARCH METHODOLOGY

Drake and Bradford (2013) indicated that infiltration rates decline over 2y in their pervious concrete pavement (PC) by 50%, permeable paver denoted EO by 85-90% and another denoted AP by 75-85%, whereas recovery by sweeping improved infiltration rates by 10% in CP, 180% in EO and 25% in AP. Clearly, only a long-term computation would clarify which paver might be best. An obvious explanation for these trends is that narrow joints are simply harder to clean, and this fact emerged as a critical concern, as will be seen in the next paragraph.

Original infiltration tests were conducted by the present authors on UNI-Ecostone with relatively large rectangular voids, 38mm x 50mm. Today the industry is faced with a new requirement: the rigorous American Disability Act (ADA). ADA stipulates that a pavement may not have gaps wider than ½" (13mm). Obviously this obligation limits the maximum width of infiltration cupules and increases the difficulty of maintaining adequate long term infiltration rates on conforming PICPs, especially if a strict maintenance scheduled is not followed. Furthermore where PICPs are mass produced, manufacturing itself imposes severe constraints.

Based on all of the foregoing we decided to proceed with laboratory-scale tests on rapidly cleanable PICPs swept and cleaned by a simulated pick-up head with air flow patterns and speeds similar to industry regenerative-air street cleaners.

Earlier work reviewed above suggested the possible suitability of regenerative air street sweepers, now the second-most popular street cleaning equipment. Air flow rates for such equipment is approximately 20,000 ft^3/min. In the rig developed for this paper, at an airflow of 200 ft^3/min. air velocities in the simulated pick-up head are matched by scaling down the length of the air supply slot.

If there is anything original in this present work, it is the special-purpose design of PICPs for rapid restoration of infiltration rates by conventional street sweeping equipment. We denote the new special PICPs “RCPP”.

TEST RIG, TEST PICPS AND DISCUSSION

A number of test RCPPs were machined in poplar, as shown in Figure 3. A single RCPP was inserted in the plexiglass rectangular container called the “ampule” herein. Bedding, conduit and cupule filter media were poured into the ampule, the RCPP tamped down and the assembly paced in the test rig, depicted in Figure 2. Connected to the regenerative air source, the test pick-up head passed over the RCPP at speed, as can be discerned from Figure 2, which shows our test version of a regenerative air pick-up head. Results for the tests in the laboratory rig show that, for the chosen geometries, virtually complete removal $S \cong 1.0$, or even excessive removal $S \geq 1.0$ is easily achieved at almost any reasonable speed V. Figure 3 shows one such result.

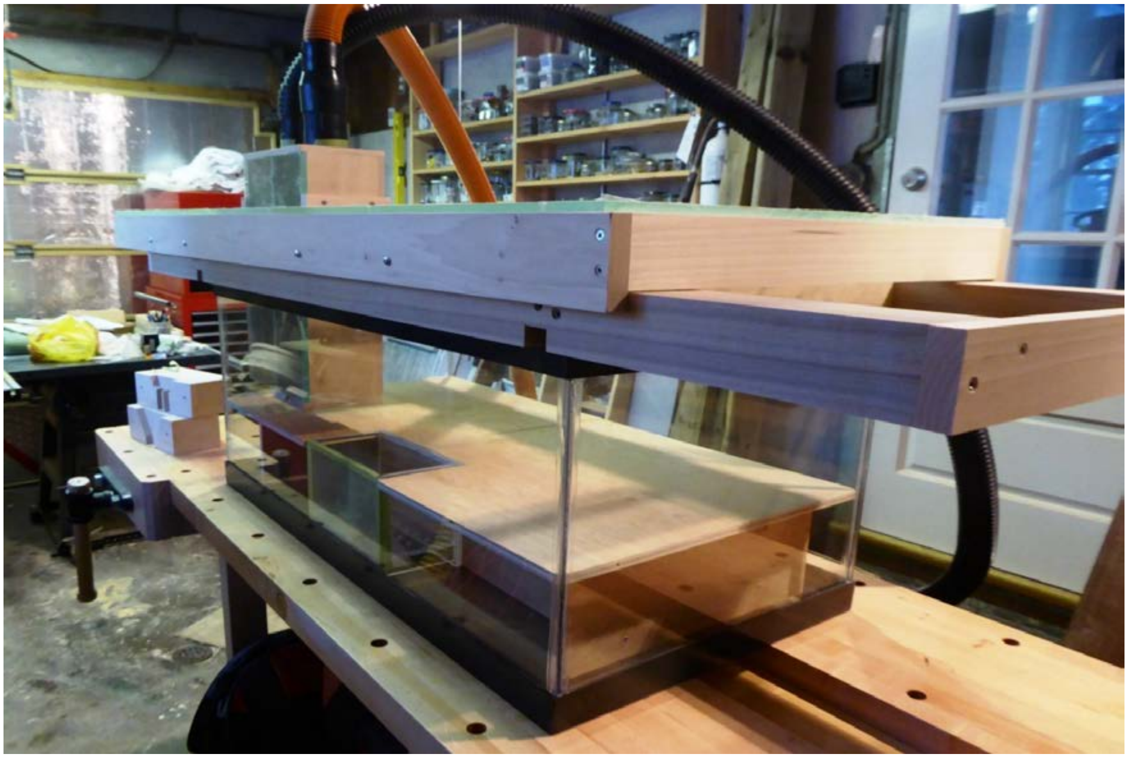

Figure 2 Rig, general arrangement.

Figure 3 Cleaned PICP, V approx. 15km/h.

CONCLUSIONS

Real life experience with existing street cleaners and PICPs has been disappointing, with conventional sweepers generating limited cleaning depths, and only partly restoring infiltration rates, even though clogging of drainage cells in PICPs is mostly in the upper layers of the filter media. New RCPPs, designed for rapid cleaning and restoration of infiltration rates by conventional regenerative-air street sweeping equipment, are described. The performance of the new RCPP is demonstrated using a purpose-built laboratory rig. Conduits in the RCPPs provide the required controlled drainage flows, and the blocks meet safety standards for people with disabilities and other users, as well as certain unstated criteria for mass production.

ACKNOWLEDGEMENTS

Information in this paper has been published in fuller detail in the Journal of Water Management Modelling (https://www.chijournal.org/. Neither is a final report on comprehensive, completed field trials, but a description of initial experiments that prove the concepts. Field trials are planned during 2016. Experiments were conducted on a test rig and sample RCPP blocks designed, built and tested by Bill. Patents pending. Sand and grit was kindly supplied by Mark Latyn of Capital Paving Inc. and by Jeff Oravecz, Coloured Aggregates Inc., both in Ontario. Jeff MacDonald, Amaco Equipment, Mississauga supplied details on regenerative air sweepers.

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Most of these references are available free on the web through this open source Journal of Water Management Modeling https://www.chijournal.org/

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